INFRARED STELLAR PHOTOMETRY*

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ABSTRACT

A new system of infrared stellar photometry, with approximate effective wavelengths of 2.2 and 3.6 μ, has been established. Observational data at these two wavelengths, which are designated by K and L, and given for more than fifty stars of spectral types ranging from O5 to M6. From the combination of these new data with previously published multicolor photometry, revised effective temperatures and bolometric corrections for stars of spectral class F5 and later have been derived. The new temperatures are somewhat higher than previous ones, particularly for the early K giants and the M dwarfs; the bolometric corrections for the late-type stars are considerably smaller than those derived by Kuiper but are similar to those derived by Strömberg.

I. INTRODUCTION

The development, during the last ten or fifteen years, of infrared detectors having relatively high sensitivity has made it possible to consider stellar photometry at wavelengths much longer than 1 μ. Probably the first such photometry was that of Whitford (1948, 1958), who measured reddened and (essentially) unreddened early-type stars and interpreted his data in terms of the law of interstellar reddening. At about the same time, Felgett (1951) measured various bright stars of many different spectral types. Hiltner (Strömgren 1955) has used an infrared photometer to measure the polarization of highly reddened stars at the long wavelengths.

All three of these investigators used PbS cells and broad-band filters (or no filter at all) which isolated wavelength bands whose effective wavelengths ranged from about 1.5 to 2 μ. Recent developments in detectors and filters, however, have made possible a refinement in the observational procedures. Four wavelength bands, centered at approximately 1.3, 2.2, 3.6, and 5.0 μ, were selected; the magnitudes obtained from observations at these wavelengths are designated by J, K, L, and M, respectively. The first observations were taken in K and L, and these data are the subject matter of this paper.

II. THE PHOTOMETER

Only a general description of the photometer will be given here; a more detailed description will be published at a later date. An InSb photovoltaic detector manufactured by Texas Instruments, Inc., was used. The choice of this detector was dictated by the fact that it is the most sensitive one at the wavelength of 5 μ (magnitude M). For the shorter wavelength bands (magnitudes J and K), PbS cells are more sensitive by about 2 mag. The InSb detector is inclosed in a heavy copper box, which is immersed in liquid nitrogen to maintain the temperature at 77° K. The copper box entirely incloses the detector, except for a hole 2 mm. in diameter through which the starlight is passed. This construction offers two advantages: first, the large thermal capacity of the copper box produces relatively constant-temperature conditions for the detector; second, the complete inclosure of the detector by a low-temperature box shields it from extraneous high-temperature radiation, increasing the detector sensitivity. In actual practice, the detector stability has been quite satisfactory, and the low-temperature inclosure has brought about an increase in sensitivity of a factor of 5, compared with the more usual operating conditions.

The four wavelength bands were chosen to coincide with atmospheric transmission

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bands, and interference filters are used to isolate the regions. These filters have approximately square-top transmission bands, with the band edges at the following wavelengths: J, 1.1–1.4 μ; K, 1.9–2.5 μ; L, 3.2–4.1 μ; and M, 4.4–5.5 μ. The filters transmit approximately 70 per cent of the radiation in the pass band, and all are completely blocked on the short-wavelength side.

The incoming radiation is chopped at a frequency of 1450 cycles per second. The output of the detector is sent to an a.c. amplifier tuned to the chopping frequency, followed by a synchronous detector and a d.c. amplifier. For some of the observations, a capacitor-charging integrator (Gardiner and Johnson 1955) was used.

III. THE OBSERVATIONS

When the infrared photometer was first put into operation (January, 1961) only the filters for magnitudes K and L were available; thus this first report of data from the new photometer is confined to those two magnitudes. Sufficient new results are now available to justify this preliminary discussion; nevertheless, additional information may be expected from observations in the other two magnitudes (J and M).

Observations in K and L have been made on more than fifty stars of spectral type ranging from O5 to M6. Both giants and dwarfs are included. The zero points of the new magnitude scales have been chosen in agreement with those of the U, B, V system (Johnson and Morgan 1953); i.e., all magnitudes are the same for stars of spectral type A0 V. The observations are listed in Table 1, where the first column contains the star name; the second, the HD number; the third, the spectral type from Keenan and Morgan (1951) or Eggen (1955); the fourth and fifth, the magnitudes, K, and the colors, $K - L$; and the last column, the quality of the photometric data. Quality 1 indicates well-observed stars; quality 2, two to four accordant observations; quality 3, poorer data or (regardless of the apparent quality) a single observation. A colon following a value of $K - L$ indicates that this value is actually of lower quality than indicated in the last column; this number then applies only to the magnitude K.

From the values of K listed in Table 1 and previously observed values of the magnitude V (Johnson and Morgan 1953; Johnson and Harris 1954; Eggen 1955; Johnson 1955; Hiltner and Johnson 1956) a color index, $V - K$, may be computed. In Figure 1, $V - K$ is compared with $B - V$. (For four stars, μ UMa, 2 Cen, θ Cen, and HR 5299, $B - V$ was computed from Eggen's (1955) $P - V$; my unpublished U, B, V data were used for α And, ρ Per, β Aur, and β Peg.) The correlation between $V - K$ and $B - V$ is good, for $B - V < 1.40$. There is some scatter about the mean line, but not all of this can be accounted for by the observational errors. It is of interest that the coolest stars observed—2 Cen and HR 5299—are actually bluer in $B - V$ than other, warmer stars. Also, there is a change in the slope of the relationship between the two-color indices at just about the position of the sun ($B - V = +0.63$) in the diagram. In general, Figure 1 indicates that the infrared data are of good quality; in particular, the agreement near $B - V = 0.00$ indicates that the InSb detector and amplifier are linear, since the stars at this color have magnitudes which differ by as much as 3.5 mag. Since the color index, $V - K$, is the difference between two independently observed magnitude systems, the agreement in $V - K$ indicates that the two magnitude scales are the same.

IV. STELLAR SPECTRAL ENERGY DISTRIBUTIONS

The combination of the data of Table 1 with U, B, V photometry (references listed in Sec. III), the *Six-Color Photometry* (Stebbins and Kron 1956) and *R, I Photometry* (Kron, White, and Gascoigne 1953; Kron and Gascoigne 1953; Kron and Mayall 1960) permits the derivation of stellar spectral energy comparisons over a much greater wavelength range than ever before. Such comparisons for stars selected from Table 1 are shown in Figures 2 and 3. The standard to which these curves are normalized is the sun; i.e., the

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TABLE 1

THE PHOTOMETRIC DATA

Star Name	HD	Sp	*K*	*K—L*	Quality
α And	358	(B8 p)	+2 46	. .	3
β Cas	432	F2 IV	+1 41	−0 05	3
χ Peg	1013	M2 III	+0 67	+ 04:	2
α Ari	12929	K2 III	−0 61	+ 12	Std
ρ Per	19058	.	−1 90		3
HR483 . .	10307	G2 V	+3 39	. . .	2
α Per	20902	F5 I*b*	+0 59	+ 03	1
ε Eri	22049	K2 V	+1 72	+ 20	3
α Eri	25025	. . . .	−0 91	. .	3
δ Tau	27697	K0 III	+1 50		3
α Tau	29139	K5 III	−2 82	+ 22	Std
α Aur. .	34029	G8 III+F	−1 78	+ 06	2
β Ori	34085	B8 Ia	+0 19	− 10	2
γ Ori .	35468	B2 III	+2.12	. .	3
α Lep	36673	F0 I*b*	+1 99		3
α Ori .	39801	M2–M3 I*ab*	−4 16	+ 31	1 (variable)
β Aur	40183	A2 IV	+1 94	. .	3
γ Gem	47105	A0 IV	+1.92	+ 17:	2
α CMa	48915	A1 V	−1 38	+ 05	2
α Gem	60178	Am+A1 V	+1 46		3
α CMi . .	61421	F5 IV	−0 69	+ 07	2
β Gem .	62509	K0 III	−1 09	+ 13	Std
ζ Pup	66811	O5f	+3 07	.	3
β Cnc	69267	K4 III	+0 15	+ 09	2
α Leo	87901	B7 V	+1 66	− 05: :	1
γ Leo .	89484	K0 IIIp	−0 65	+ 14	2
μ UMa . .	89758	M0 III	−0 79	+ 12	3
α UMa. .	95689	K0 III	−0 59	+ 15	2
Lal 21185	95735	M2 V	+3 79	+ 23	3
γ V'r	110379	. . . .	+2 02		2
β Com .	114710	G0 V	+2 77	+ 22	2
Barnard's star .	+4°3561	M5 V	+4 88	. .	2
α Vir	116658	B2 V	+1 61	− 21	2
2 Cen	120323	sgM6	−1 65	+ 20	2
η Boo	121370	G0 IV	+1 42	− 01	2
θ Cen	123139	K0 III–IV	−0 23	+ 13	3
HR5299	123657	gM4	−0 26	+ 28	2
α Boo	124897	K2 IIIp	−3 03	+ 13	Std
σ Ser	140573	K3 III	+0 13	+ 11	2
ε CrB	143107	K3 III	+1 35	+ 12	3
α Sco	148478	Comp	−3 83	+ 32	2
ζ Her	150680	G0 IV	+1 32	− 16	2
β Oph .	161096	K2 III	+0.23	+ 13	1
γ Dra	164058	K5 III	−1 25	+ 19	1
α Lyr	172167	A0 V	+0 02	+ 04	1
β Cyg	183912	Comp.	+0 21	+ 06	2
σ Dra	185144	K0 V	+2 90	+ .23	3
61 Cyg B	201092	K5 V	+2.76	+ 01:	2
α Aql	187642	A7 IV, V	+0 25	+ 06	2
α Cyg	197345	A2 Ia	+0 93	+ 08	2
ε Cyg	197989	K0 III	+0.17	+ .10	Std
β Peg	217906	M2 II–III	−2 10	+0.25	1

sun would, on these diagrams, have a horizontal straight line at Δ mag. = 0.00. The sun has not actually been observed on any of the photometric systems used in the construction of Figures 2 and 3, but its colors can be inferred from its spectral type, G2 V, and from its colors measured with respect to a number of other stars, particularly HR 483 (Stebbins and Kron 1957). An I measure was obtained with the InSb photometer for χ Peg, for which no such observations have been published. This was done also for β Peg, in order to make it possible to plot the curve in Figure 3 from colors alone, without regard to the variable magnitude of this star. (It so happens, however, that $V - K$ computed from V and K magnitudes measured at very different times is essentially the same as indicated by the curve of Fig. 3.)

There are certain differences between dwarfs and giants, as illustrated in these two diagrams. For example, in the giants, L appears to be somewhat fainter compared with K than in the dwarfs. Also, late-type dwarfs seem to be fainter in K than are giants for the same color in the wavelengths 0.5–1.0 μ; put another way, late-type dwarfs seem to have a large excess of radiation, compared with giants, in the region around 1.0 μ. The extension of the observations to the longer wavelengths has shown up deviations from black-body radiation that were not readily apparent from the *Six-Color Photometry* (Stebbins and Whitford 1945; Stebbins and Kron 1956).

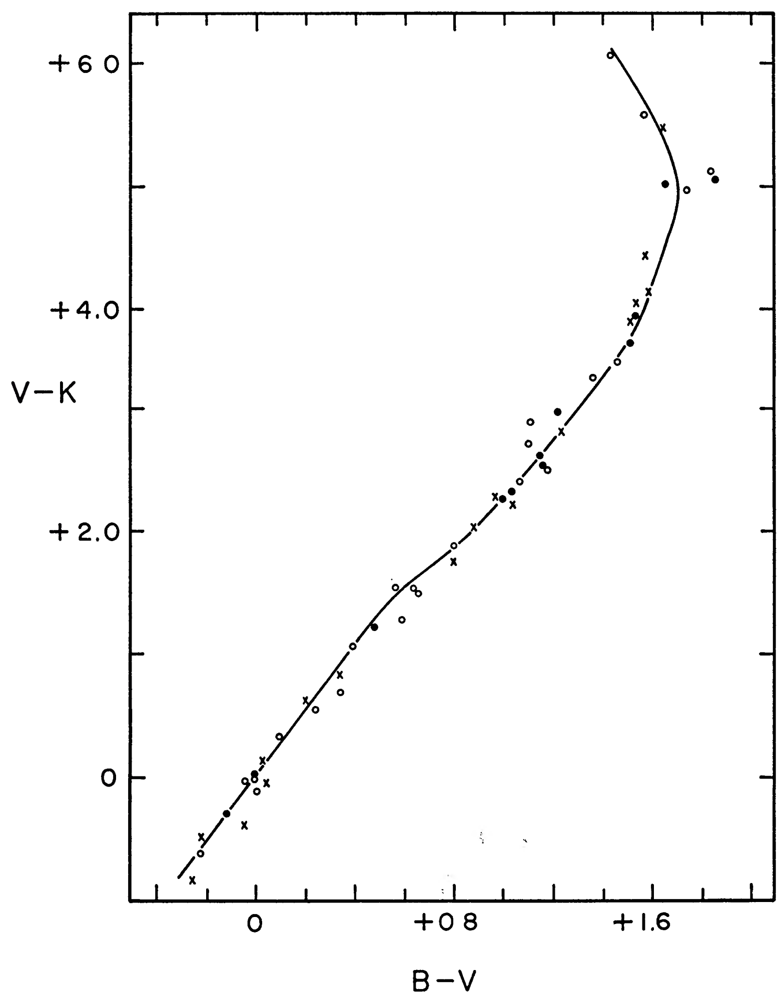

FIG. 1 —The relationship between $V - K$ and $B - V$. The filled circles, open circles, and crosses represent data qualities (see Table 1) 1, 2, and 3, respectively.

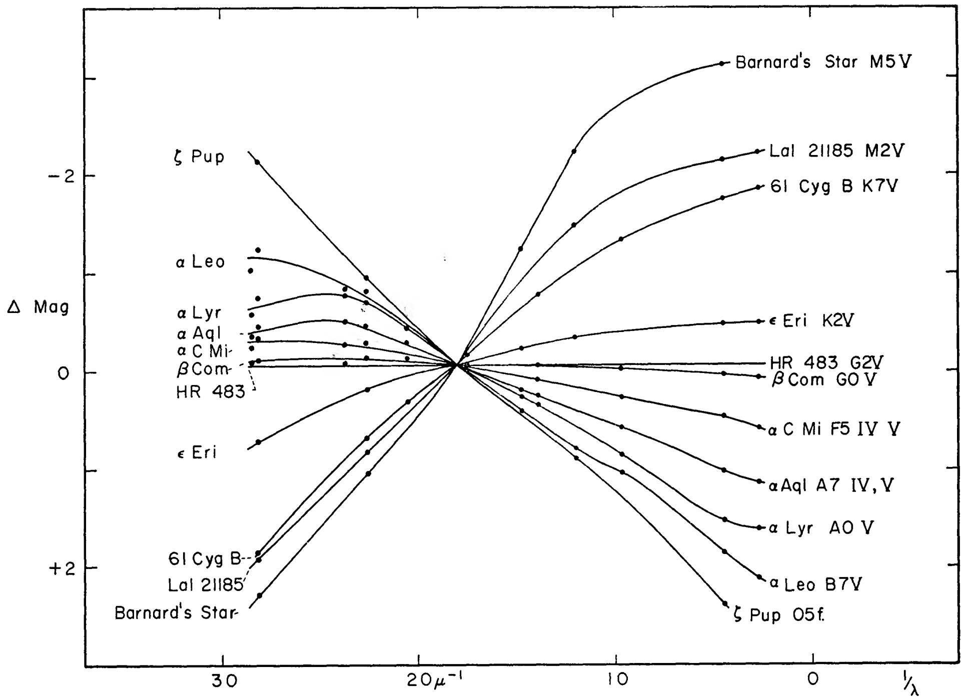

FIG. 2.—The spectral energy-curves for dwarfs

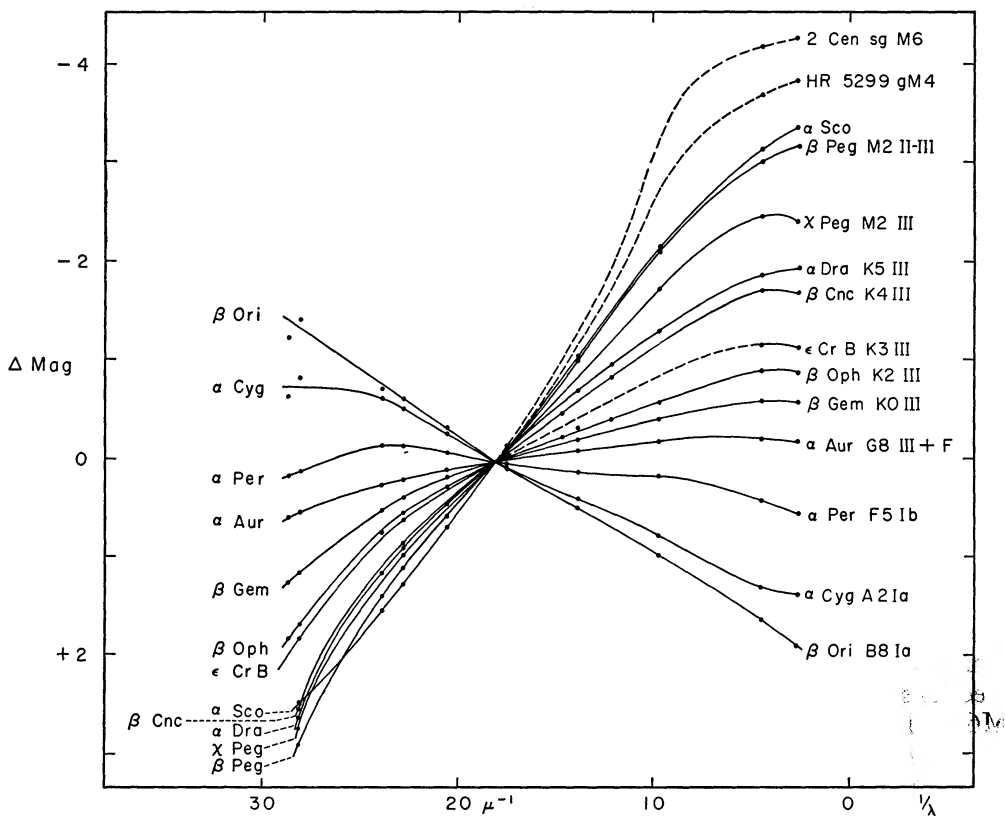

FIG. 3.—The spectral energy-curves for giants

It is of interest to attempt to determine stellar effective temperatures from the data that are now available. An examination of Figures 2 and 3 shows that the color index, $V - K$, may be used as an approximation to the average gradient for the stars. Color temperatures computed from $V - K$ might be expected, therefore, to be reasonably close to the effective temperatures. Color temperatures, computed on the assumptions that the sun's effective temperature is 5785° K (Allen 1955) and that the differences between the sun and the other stars may be described by the black-body curve, are listed in Table 2. Such temperatures will be too low (by a few per cent) for stars such as Barnard's Star, which has a large excess of radiation at 1.0 μ compared with a black body. The temperatures of Table 2 are higher than those given by Kuiper (1938) or by Keenan and Morgan (1951), particularly for the early K giants and the late M dwarfs. However, Limber (1958) has argued that Kuiper's temperatures are too low, specifically for M4 V; we note that the temperature interpolated from Table 2 for M4 V is almost exactly the same as Limber's inferred temperature—3200° K. The temperature for M4 III has been derived on the assumption that the spectral type of HR 5299, gM4 (Eggen 1955), may be taken as M4 III.

TABLE 2

STELLAR TEMPERATURES

Sp	T	Sp.	T	Sp.	T
F5........	7000°				
G0 V.........	5850°				
G2 V.........	5785°				
G8 V.........	5570°	G8 III.......	4970°		
K0 V.........	5300°	K0 III.......	4810°		
K2 V.........	5060°	K2 III.......	4380°		
K5 V.........	4330°	K5 III.......	3600°		
M0 V.........	3800°	M0 III......	3500°		
M2 V.........	3500°	M2 III.......	3250°	M0–2 I*b*.....	(3000°)
M5 V.........	3000°	M4 III.......	(2750°)		

V. BOLOMETRIC CORRECTIONS

Since the spectral energy distribution-curves of Figures 2 and 3 extend to the infrared well beyond the maxima of any of the stars, they suggest the possibility of computing the bolometric corrections, by integrating the stellar energy-curves (on an intensity basis). Accordingly, the stellar intensity-curves were computed, and the areas under the curves, relative to that of the sun, were obtained. In these computations, the solar spectral intensity-curve of Allen (1955) was used, smoothed to approximate the effect of the broad-band filters. The smoothing is not important, however, since essentially the same result would have been obtained if Allen's curve were used unsmoothed. The derived bolometric corrections for the various spectral types are given in Table 3. The individual bolometric corrections, B.C., are plotted against $V - K$ in Figure 4 and against spectral type in Figure 5. In order to derive bolometric corrections for 2 Cen and HR 5299, it was necessary to interpolate the dotted lines in Figure 3; when actual data become available for these two stars, these interpolated lines might be moved and the derived bolometric corrections modified as a result. It has also been assumed that spectral types gM4 and sgM6 for HR 5299 and 2 Cen, respectively (Eggen 1955), can be equated to M4 III and M6 III; this may not be true, particularly, for 2 Cen. Clearly, we need more data here.

Limber (1958) has argued that Kuiper's extrapolated bolometric corrections are too large, and he suggests values for M4 V ranging from -1.75 to -2.3; the value for this spectral type from Table 3 is −1.8 mag. The corrections given in Table 3 are in better agreement with those derived by Strömberg (1946) from the original data of Pettit and Nicholson (1928) than they are with those of Kuiper (1938).

The relationships between $V - K$ and B.C. that are shown in Figure 4 permit determination of the relationship between effective temperature and B.C. This relationship is given in Table 4, in which the first column lists the temperature; the second, the values of B.C. for giants from the curve of Figure 4; the third, the computed black-body bolometric corrections from Table 4 of Kuiper (1938); and the last column, the differences, observed *minus* computed. It is evident that the bolometric corrections that we have

TABLE 3

BOLOMETRIC CORRECTIONS

Sp	B C	Sp	B C.	Sp	B C.
F5 V .	+0 05			F5 I .	+0 1
G0 V	0 0				
G2 V	0 0				
G8 V .	0 0	G8 III ...	−0 1		
K0 V.	−0 1	K0 III	−0 2		
K2 V	−0 2	K2 III. .	−0 4		
K5 V	−0 6	K5 III	−0 9		
M0 V ..	−1 0	M0 III ...	−1 1		
M2 V .	−1 4	M2 III ..	−1 4	M0–2 I ...	−1 8
M4 V..	−1 8	M4 III . .	(−2 0)		
M5 V .	−2 0	M6 III	(−2 7)		

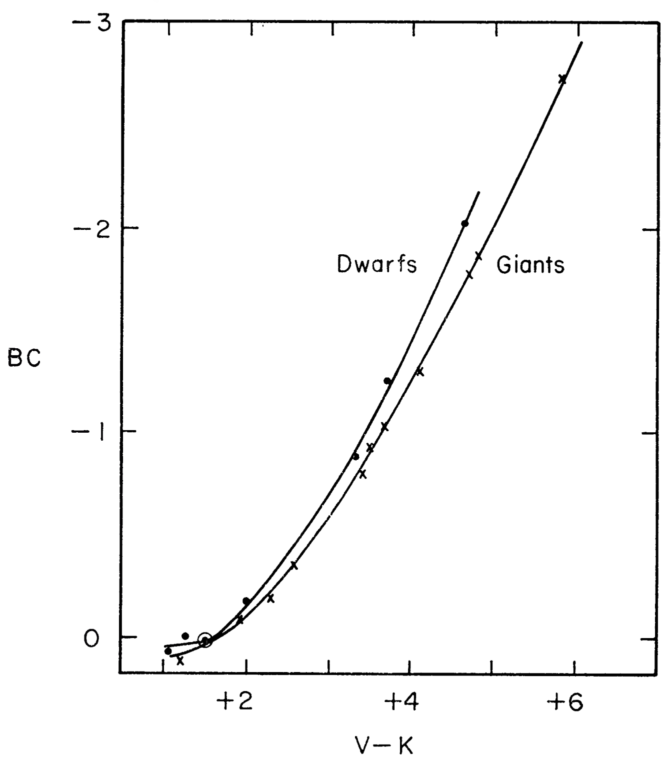

FIG. 4.—The relationship between B.C. and $V - K$

derived for giants are very similar to those computed for black bodies. The bolometric corrections for dwarfs are larger than for giants of the same temperature, as would be expected from the excess of radiation at 1.0 μ wavelength in the dwarfs.

VI. SUMMARY

In this paper are presented new photometric data for magnitudes K and L at approximate effective wavelengths of 2.2 and 3.6 μ. These data have been interpreted in terms of the stellar spectral energy distributions, the effective temperatures, and the bolometric corrections. These interpretations depend, first, upon the assumption that the values for all intermediate wavelengths may safely be interpolated between the points that have been observed. Future observations of magnitude J, at effective wavelength

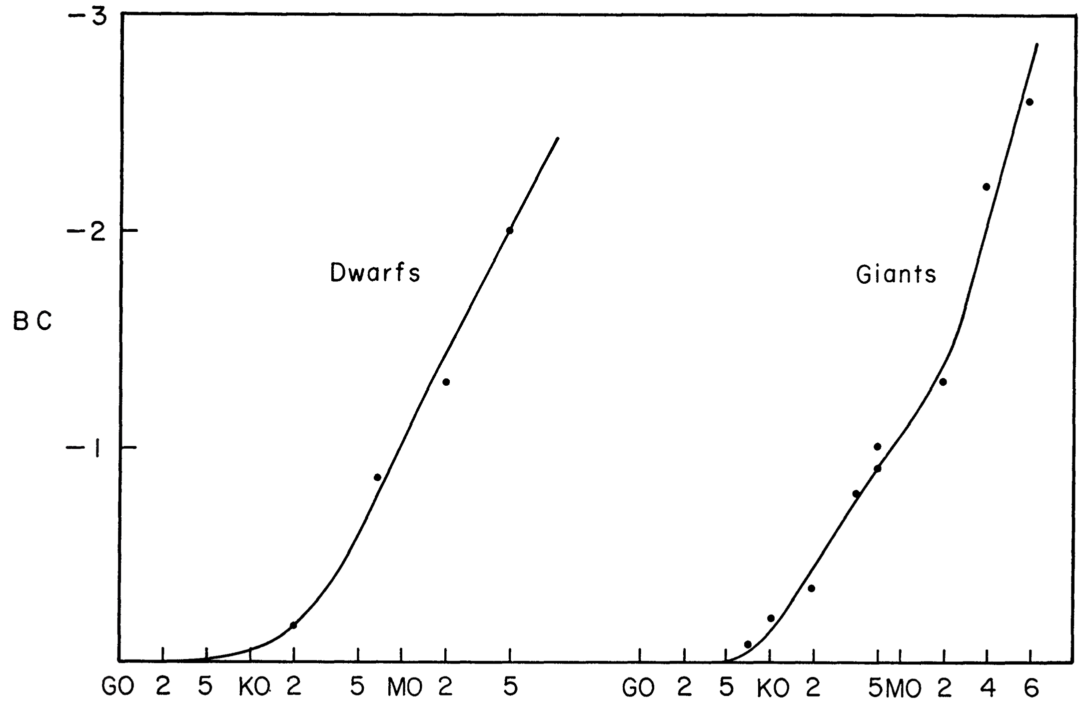

FIG. 5.—The relationship between B C. and spectral type

TABLE 4

BOLOMETRIC CORRECTIONS

T	Observed	B C Comp for Black Body (Kuiper 1938)	O—C
2500°	−2 89	−2.84	−0 05
3000°	−1 79	−1.74	− 05
3500°	−1.10	−1 07	− 03
4000°	−0.65	−0 64	− 01
4500°	−0 34	−0 36	+ 02
5000°	−0 16	−0 18	+ 02
6000°	+0 04	−0 02	+ 06
7000°	+0 09	−0 04	+0 13

1.3 μ, will strengthen or modify the interpretations that we have made here. But there is the further point that, as emphasized by Limber (1958), cool stars may have significant water-vapor absorptions in their spectra. We have, of course, deliberately avoided such spectral regions because of the atmospheric water vapor, and, for this reason, the interpolations for wavelengths between the observed points may be in error. However, the fact that the observed bolometric corrections agree so well with theoretical black-body corrections argues against a significant error due to water-vapor absorption in the stars.

This is the first report of a photometric project that has just been begun. It has, however, seemed profitable to publish the results that have so far been obtained and the interpretations that can be made. While future additional data will, no doubt, dictate modifications in these interpretations, it does not seem likely that large changes in the derived bolometric corrections or effective temperatures will have to be made at that time.

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